Enhanced erosion: New measurements and modeling

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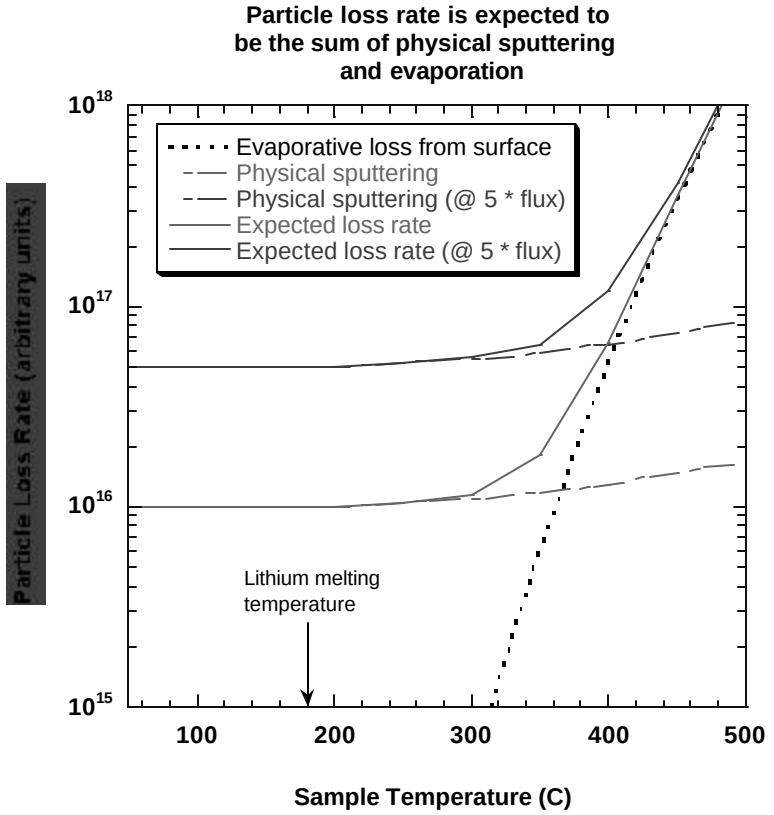
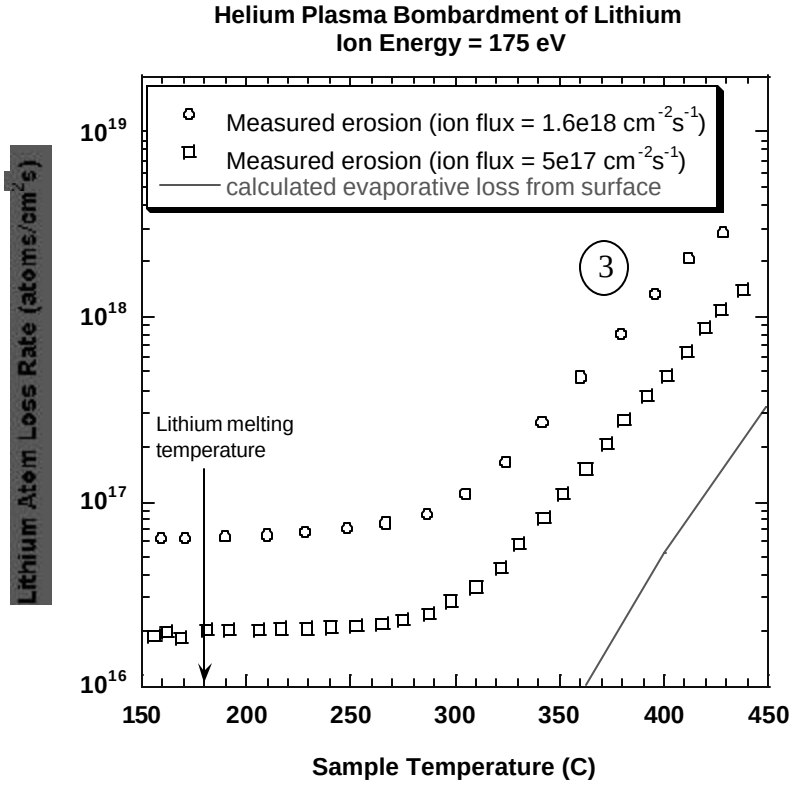
Temperature Dependent Sputtering (Review):

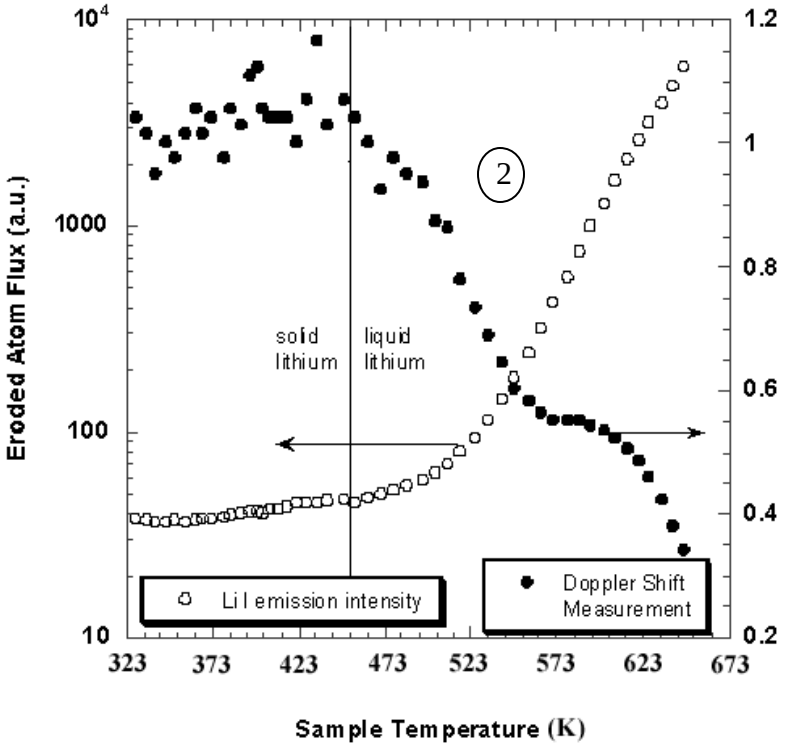
PISCES experiments show qualitative agreement with expectations, but quantitatively show enhanced erosion at high temperature.

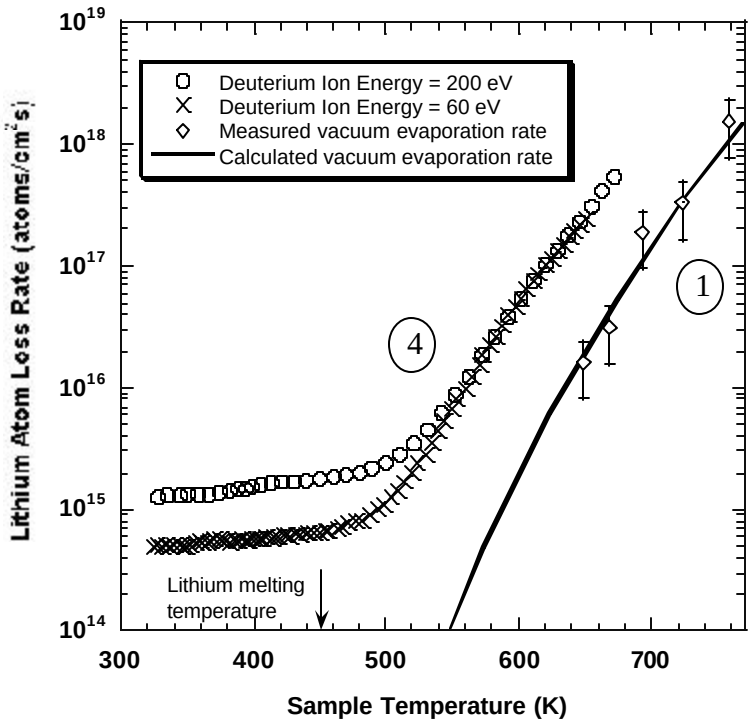




Temperature Dependent Sputtering (Review):

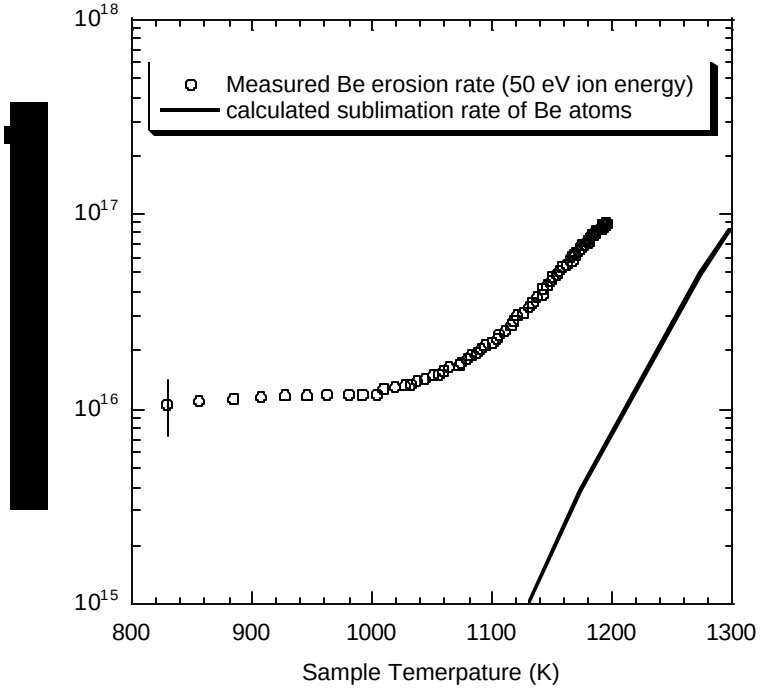
Decrease in average ejection energy of particles accompanies the increase in erosion rate, implying enhanced evaporation.





Enhanced erosion is not just an oddity of plasma-liquid surface interactions.

Solid Beryllium Samples also Exhibit Enhanced Erosion at High Temperature



- As machines proceed to longer pulses and higher energies, the impact of this effect will become more important
- Developing a model to understand the fundamental physics involved is crucial

Enhanced erosion at elevated temperature is a universal phenomenon.

- R.S. Nelson first observed enhanced erosion (of Bi, Zn, Ag, Cu, Au, Ge) in the early 1960s, and tried to explain the results using thermal spike models [R.S. Nelson, Philos. Mag. 11 (1965) 291.]
- PISCES results first showed enhanced erosion from liquid metal surfaces, but also now seen from solids [R.P. Doerner, PSI-14 & PSI-15]
- U. of Illinois saw similar enhanced erosion of liquid metal surfaces [J.P. Allain, PSI-15]
- Enhanced erosion also observed from hot W [E.P. Vaulin et al., Sov. J. Plasma Phys. 7 (1981) 239.]
- Carbon enhanced erosion led to RES theory [papers by V. Phillips and J. Roth]

Energetic particle bombardment of surfaces results not only in sputtering, but also in the creation of surface adatoms.

- We propose a surface sublimation model (either solid or liquid surface) during particle bombardment that includes the effects of adatom sublimation/evaporation.

The total atom loss rate from a surface is written

$$J_{total}(T) = J_{pl} Y_s + J_o(T) + J_{ad}??\,?$$

where, $J_{pl} Y_s$ is the sputtered particle flux

J_o is the flux of lattice atoms evaporated $\quad J_o = \frac{kn_o}{?} v_{th} \exp^{(-E_o/T)}$

J_{ad} is the adatom evaporative flux $\quad J_{ad} = \frac{kn_{ad}}{?} v_{th} \exp^{(-E_{ad}/T)}$

And the areal density of adatoms is $\quad n_{ad} = Y_{ad} J_{pl} t_{ad}$

Y_{ad} is of order unity H. Gades and H. M. Urbassek, Phys. Rev. B **50** (1994) 11167.

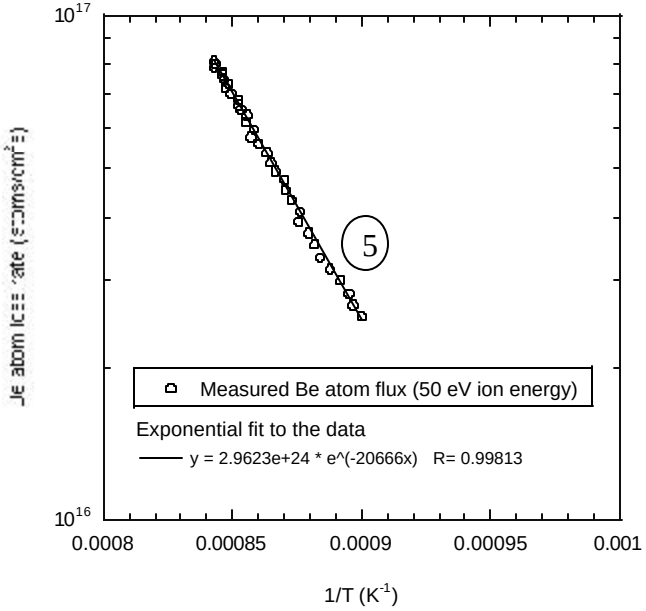
Adatoms are less strongly bound to the surface and, therefore, can be thermally released at a lower temperature.

There are two unknowns, E_{ad} and t_{ad} in the model

Arrhenius plot of high temperature data provides E_{ad}

The total loss rate, J_{total}, can be evaluated at a single temperature to calculate t_{ad}

$$J_{total} = J_{pl} Y_s \; ? \; \frac{k Y_{ad} J_{pl} t_{ad}}{?} v_{th} \exp^{(-E_{ad}/T)} \; ? \; \frac{k n_o}{?} v_{th} \exp^{(-E_o/T)}$$



Now plot temperature dependent total loss rate from surface

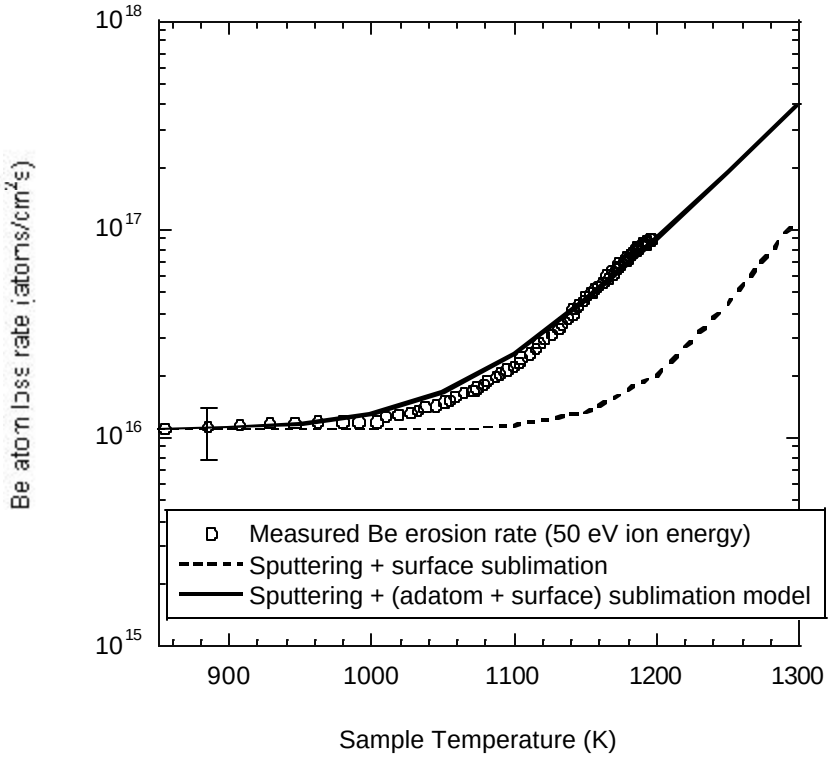
$$J_{total}(T) = J_{pl} Y_s + J_o(T) + J_{ad} ?? ?$$

for Be

E_{ad} ~ 20700 K (1.8 eV)

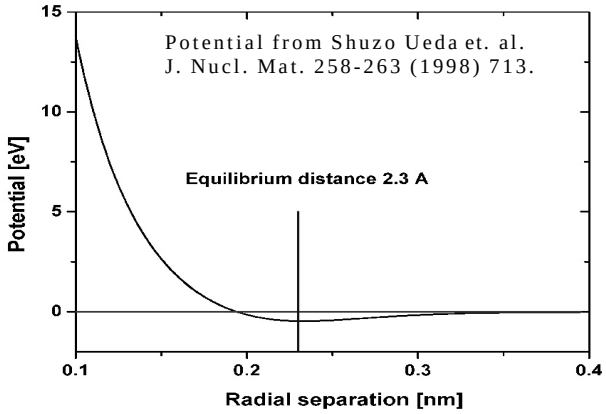
E_o ~ 38000 K (3.2 eV)

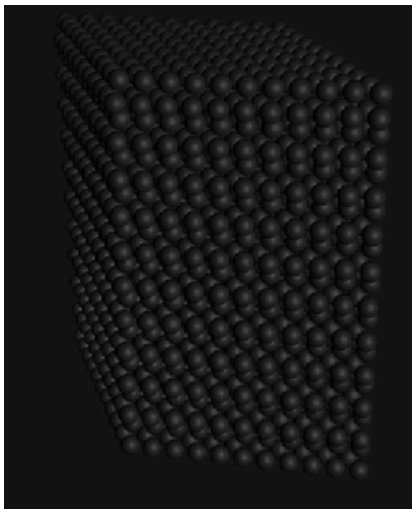
Adatom sublimation model accurately predicts loss rate across the entire temperature range.



- Adatom sublimation must be included to account for loss rate during energetic particle bombardment
- Adatom density goes to zero when energetic particle flux is removed and thermodynamic equilibrium sublimation is recovered
- Is E_{ad} = 20,700 K (1.8 eV) reasonable?

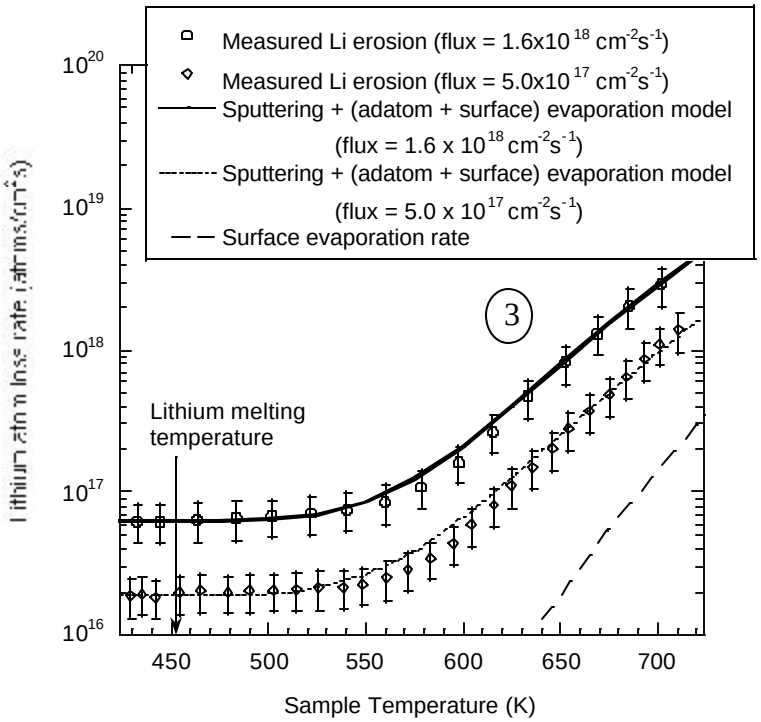
Molecular dynamics simulation is used to calculate beryllium adatom binding energy.





- A Be crystal is created using a MD simulation
- A Be adatom is then arbitrarily placed on the surface of the crystal
- The adatom is then tracked for 20 ps (in 5 fs steps) at 300K and the average binding energy is evaluated to be 1.93048 eV.
- Recall measured E_{ad} = 1.8 eV!

Adatom evaporation can also predict enhanced erosion of lithium samples, using the same model.



- Lithium E_{ad} = 12,350 K (1.1 eV)
  [Li E_o = 18,500 K = 1.6 eV]
- $J_{total}(T) = J_{pl} Y_s + J_o(T) + J_{ad}$???

  $n_{ad} = Y_{ad} J_{pl} t_{ad}$
- Only plasma flux is varied during the adatom evaporation modeling of the lithium data
- No MD simulation available yet, but Li_2 disassociation energy is 12,700 K [C. H. Wu, J. Chem.Phys. **65**, 8 (1976) 3181]

Radiation Activated Adatom Sublimation (RAAS) model explains both solid and liquid enhanced erosion at elevated temperature.

- Effect disappears when energetic particle flux is removed, as measured (1)
- Adatom model involves thermally released particles, as measured (2)
- Y_{tot} scales correctly with incident PISCES plasma flux (3)
- Y_{ad} is fairly insensitive to E_{ion} at low incident energy, consistent with PISCES data [H. Gades and H. M. Urbassek, Phys. Rev. B **50** (1994) 11167.] (4)
- Measured E_{ad} agrees with MD calculation of Be adatom binding energy (5)
- May also explain carbon enhanced erosion at high temperature (which currently is explained within the framework of RES theory)